

From the Southern Association for Vascular Surgery

# Subclavian revascularization in the age of thoracic endovascular aortic repair and comparison of outcomes in patients with occlusive disease

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**Objective:** Open surgical revascularization for subclavian artery occlusive disease (OD) has largely been supplanted by endovascular treatment despite the excellent long-term patency of bypass. The indications for carotid-subclavian bypass (C-SBP) and subclavian transposition (ST) have been recently expanded with the widespread application of thoracic endovascular aortic repair (TEVAR), primarily to augment proximal landing zones or treat endovascular failures. This study was performed to determine the outcomes of patients undergoing C-SBP/ST in the context of contemporary endovascular therapies and evolving indications.

**Methods:** A prospective database including all procedures performed at a single institution from 2002 to 2012 was retrospectively queried for patients who underwent subclavian revascularization for TEVAR or OD indications. Patient demographics and perioperative outcomes were recorded. Patency was determined by computed tomography angiography in the TEVAR group. Noninvasive studies were used for the OD patients. Life-table methods were used to estimate patency, reintervention, and survival.

**Results:** Of 139 procedures identified, 101 were performed for TEVAR and 38 for OD. All TEVAR patients underwent C-SBP/ST to augment landing zones (49% preoperative; 41% intraoperative), treat arm ischemia (8% postoperative), or for internal mammary artery salvage (2%). OD patients had a variety of indications, including failed stent/arm fatigue, 49%; asymptomatic >80% internal carotid stenosis with concurrent subclavian occlusion, 18%; symptomatic cerebrovascular OD, 13%; redo bypass, 8%; and coronary-subclavian steal, 5%. Differences in postoperative stroke and death, primary patency, or freedom from reintervention were not significant. The 30-day postoperative stroke, death, and combined stroke/death rates were, respectively, 10.8%, 5.8%, and 13.7% for the entire cohort; 8.9%, 7.1%, and 12.9% in TEVAR patients; and 15.8%, 2.6%, and 15.8% in OD patients. The 1- and 3-year primary patencies were, respectively, 94% and 94% for TEVAR and 93% and 73% for OD patients. Survival was similar between the groups, with an estimated survival rate of 88% at 1 year and 76% at 5 years.

**Conclusions:** Stroke risk in this contemporary series of C-SBP/ST performed for TEVAR and OD indications may be higher than previously reported in historical series. In TEVAR patients, this may be attributed to procedural complexity of the TEVAR in patients requiring subclavian revascularization. In OD patients, this is likely due to the changing patient population that requires more frequent concomitant carotid interventions. Despite the short-term morbidity, excellent bypass durability and equivalent long-term patient survival can be anticipated. (J Vasc Surg 2013;58:901-9.)

Subclavian revascularization has historically been performed on patients with peripheral arterial occlusive disease (OD) presenting with arm ischemia, vertebrobasilar insufficiency, a threatened left internal mammary artery bypass graft, or failing ipsilateral hemodialysis access.<sup>1,2</sup> Reports published >2 decades ago, before the endovascular era, demonstrated that carotid-subclavian bypass (C-SBP) or subclavian transposition (ST) could be performed with

a 0% to 6% perioperative stroke risk and a 5-year primary patency rate of 82% to 95%,<sup>3-5</sup> with slightly higher rates of perioperative mortality and stroke (4% to 8%) in patients requiring concomitant revascularization of the carotid bulb or vertebral artery, or both.<sup>6-8</sup> Introduction of angioplasty or stent treatment of subclavian artery OD led to a shift in the mid-1990s to the use of open surgical reconstruction for interventional failures or more complex anatomic considerations such as preservation of a dominant vertebral artery, left internal mammary artery graft adjacent to occlusion, or simultaneous severe extracranial carotid or vertebral OD.<sup>9,10</sup>

As the relative frequency of open surgical reconstruction of subclavian OD has decreased in contemporary practice,<sup>10</sup> the emergence of thoracic endovascular aortic repair (TEVAR) has expanded the indications for subclavian revascularization. Although not based on definitive data, current consensus guidelines for elective TEVAR recommend routine preoperative subclavian revascularization when covering the left subclavian artery (LSA).<sup>11</sup> Subclavian coverage augments the proximal landing zone, and revascularization may decrease the risks associated with

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this coverage, including anterior/posterior stroke, arm ischemia, and spinal cord ischemia.<sup>11,12</sup>

Although subclavian revascularization is reported to potentially decrease some of the risks associated with coverage of the subclavian artery, the bypass itself may increase the risk of stroke, and few series have focused on the short-term morbidity and outcomes specifically attributed to the subclavian revascularization in TEVAR.<sup>13</sup> Because of the evolving role of subclavian revascularization for both OD and TEVAR, this study was undertaken to determine the contemporary perioperative and long-term outcomes of patients undergoing C-SBP/ST for TEVAR and OD in the era of endovascular therapies.

## METHODS

Approval for this study was obtained from the University of Florida College of Medicine Institutional Review Board.

**Database and patient cohorts.** A prospectively maintained operative registry at the University of Florida was retrospectively queried for all open cervical revascularization procedures (bypass or transposition) involving the subclavian artery for any indication from July 2002 to June 2012. The analysis included patients with combined carotid and subclavian OD, innominate lesions, or complex reconstructions such as C-SBP with concomitant carotid endarterectomy (CEA). This included patients with extracranial cerebrovascular arterial OD who would require subclavian-carotid revascularization or vice versa. Patients treated for OD with percutaneous angioplasty or stent placement, or both, were evaluated *only* if they subsequently required open surgical reconstruction; otherwise, patients with isolated endovascular subclavian artery revascularization were excluded. Patients who underwent open subclavian revascularization as an adjunct to TEVAR were also analyzed. We reviewed 607 TEVAR patients, and identified 101 (16.6%) who had required subclavian revascularization. Patients who underwent cardiopulmonary bypass/circulatory arrest for arch replacement were excluded; however, patients undergoing sternotomy with innominate/carotid bypass performed at a separate setting from TEVAR with subclavian revascularization were included.

Demographics, comorbidities, procedure-related details, postoperative reintervention, and medication history were recorded retrospectively. Comorbidities and complications were defined based on Society for Vascular Surgery (SVS) reporting standards.<sup>14,15</sup> Procedural adjuncts for TEVAR were tabulated and categorized according to SVS guidelines.<sup>16</sup> Adjunctive procedures for OD were defined as any endovascular or open surgical procedure that was performed in conjunction with the C-SBP/ST such as CEA or arch vessel stent. Postoperative stroke was recorded if the complication was verified by magnetic resonance imaging evidence or neurology consultation documentation, or both. All 30-day strokes due to any etiology (eg, embolic or hemorrhagic) and any distribution (anterior or posterior cerebral circulation) or location were

recorded. Mortality events were verified by query of the Social Security Death Master File. Study end points included 30-day stroke, death, combined stroke/death, all-cause mortality, graft patency, and reintervention.

**Clinical practice and operative technique.** OD patients underwent preoperative bilateral brachial and digital pressure measurements as well as wrist-brachial index and digital-brachial index calculation. Early in the experience of OD management, patients underwent preoperative computed tomography angiography (CTA) or four-vessel arch aortography, or both, at the operating surgeon's discretion. As the practice evolved, virtually all OD patients underwent preoperative CTA alone. All TEVAR patients underwent CTA with centerline reconstruction. Only selected TEVAR patients had preoperative noninvasive studies.

All C-SBP/ST procedures were performed under general anesthesia using a variety of conduit choices based on the operating surgeon's discretion. The most frequently used prosthetic conduits were 6- or 8-mm Dacron (Du Pont, Wilmington, DE) grafts (Vascutek Inc, Terumo, Ann Arbor, Mich) or 6- or 8-mm polytetrafluoroethylene grafts (Gore-Tex; W.L. Gore & Associates, Flagstaff, Ariz). In selected cases (eg, redo bypass), autogenous femoral or saphenous vein was used for reconstruction.

All patients were treated with preoperative antiplatelet therapy, typically with aspirin (81 mg/d) unless a confirmed allergy existed, and selected patients with a pre-existing cardiac stent or concern for symptomatic carotid disease were maintained on clopidogrel (75 mg/d). Additionally, patients who were not already receiving long-term statin therapy were increasingly prescribed postoperative statin therapy over time.

A supraclavicular incision was used, and permissive hypertension (mean arterial pressure  $\geq 70$  mm Hg) with systemic heparinization (100 U/kg bolus; activated clotting time goal of  $\geq 200$  seconds) was instituted before carotid clamp application. An end-to-side anastomosis to the subclavian artery distal to the origin of the vertebral artery was constructed and tunneled in a retrojugular fashion to complete an end-to-side anastomosis to the base of the common carotid artery. In cases of ST, the subclavian artery was mobilized proximal to the vertebral artery, then ligated, divided, and transposed onto the proximal common carotid artery. Protamine was administered for anticoagulation reversal at case completion in most patients. The technical adequacy of the bypass was confirmed by continuous-wave Doppler insonation and the presence of a radial pulse, if the patient did not have pre-existing forearm OD.

Postoperatively, patients underwent serial neurologic assessment in a surgical intensive care unit with arterial catheter monitoring. If a change in the preoperative neurologic examination was detected, confirmatory imaging (CT or MRI with diffusion-weighted imaging, or both) was obtained with concomitant neurology consultation.

**Follow-up protocol.** Postoperative graft surveillance included duplex scanning and pulse examination with

wrist-brachial index and digital-brachial index measurements for OD patients at 1 month, 6 months, and annually thereafter. Patients undergoing subclavian revascularization with TEVAR were assessed with a serial pulse examination and postoperative CTA that included the thoracic inlet at 1 month, 6 months, and annually thereafter, unless a radiographic abnormality dictated otherwise. Bypass grafts were considered at risk for thrombosis if a 3.5-times step-up in peak systolic velocity (PSV) was discovered (eg, highest PSV within stenosis/PSV ratio of proximal normal vessel), particularly if accompanied by a 0.15 reduction in the wrist-brachial index or a change in the pulse examination, or both. Thrombosis was verified on surveillance graft duplex scan if no flow was identified within the graft or if CTA demonstrated absence of contrast filling within the graft.

Patency definitions of the subclavian reconstruction were based on SVS reporting standards.<sup>14,16</sup> Reintervention was defined as any endovascular or open surgical procedure that required a return trip to the operating to room to treat impending graft failure or thrombosis.

**Statistical analysis.** Bivariate analysis was performed on demographics, bypass characteristics, and postoperative outcomes of OD and TEVAR patients using the Fisher exact,  $\chi^2$ , Mann-Whitney, or Student *t*-test when appropriate. Mortality, patency, and reintervention were analyzed using Kaplan-Meier life-table methodology and the Mantel-Cox log-rank test. Multivariable analysis for predictors of stroke and death was completed using stepwise logistic regression based on the Akaike information criterion. This function was bootstrapped 100 times to ensure robust variable selection, and the model was based on the variables most often chosen as informative predictors in the bootstrap runs. All data were analyzed with the R 2.15.0 software (The R Foundation for Statistical Computing, [www.r-project.org](http://www.r-project.org)), and statistical significance was assumed for *P* values < .05.

## RESULTS

Between 2002 and 2012, 139 patients were identified who underwent 144 subclavian revascularization procedures, comprising 137 bypasses and 7 transpositions. Primary indications for C-SBP/ST included atherosclerotic OD in 38 (27.3%) and a TEVAR adjunct in 101 (72.7%). Mean  $\pm$  standard deviation age was 62.5  $\pm$  12.5 years, and 50 patients (36%) were female. Significant differences in age and comorbidities were present between patients who underwent subclavian revascularization for OD vs TEVAR (Table I). No difference in postoperative antiplatelet, anticoagulant, or statin use was detected. Overall, 30-day postoperative stroke, death, and combined stroke/death rates were, respectively, 10.8% (*n* = 15), 5.8% (*n* = 8), and 13.7% (*n* = 19).

**Subclavian revascularization and TEVAR.** Of the 101 C-SBP/ST procedures performed as an adjunct to TEVAR, indication and timing included augmentation of landing zone (49% preoperatively, 41% intraoperatively), treatment of arm ischemia (8% postoperatively), or internal

**Table I.** Overall patient characteristics, medication history, and comorbidities for patients undergoing subclavian revascularization for thoracic endovascular aortic repair (TEVAR) or occlusive disease (OD) indications<sup>a</sup>

Variables <sup>b</sup>	TEVAR ( <i>n</i> = 101)	OD ( <i>n</i> = 38)	<i>P</i> <sup>c</sup>
Age, years	64 $\pm$ 12	59 $\pm$ 13	.05
Male	69 (68)	20 (63)	.09
Body mass index	29 $\pm$ 5	26 $\pm$ 4	.004
Transpositions	6 (6)	1 (3)	NA
Medications			
Antiplatelets <sup>d</sup>	97 (96)	34 (90)	.2
Anticoagulation <sup>c</sup>	13 (13)	8 (21)	.3
Statins	61 (62)	25 (66)	.7
Comorbidities			
Hypertension	89 (88)	32 (84)	.6
Dyslipidemia	45 (45)	27 (71)	.005
Smoking	43 (43)	34 (89)	.0001
Coronary artery disease	33 (33)	23 (61)	.003
COPD	17 (17)	16 (42)	.02
Diabetes mellitus	15 (15)	11 (29)	.06
Renal insufficiency	12 (12)	8 (21)	.2
Cerebrovascular disease	8 (8)	14 (37)	.0001
Peripheral arterial disease	6 (6)	20 (53)	.0001
Congestive heart failure	6 (6)	9 (24)	.005

COPD, Chronic obstructive pulmonary disease.

<sup>a</sup>As expected, the OD cohort had a higher prevalence of cardiovascular risk factors.

<sup>b</sup>Continuous data are presented as mean  $\pm$  standard deviation and categorical data as number (%).

<sup>c</sup>Fisher exact, Mann-Whitney, or  $\chi^2$  tests were used when appropriate.

<sup>d</sup>Includes aspirin, clopidogrel, or aspirin and clopidogrel.

<sup>e</sup>Includes warfarin or low-molecular-weight heparin.

mammary artery salvage (2% intraoperatively). Table II highlights procedure-specific details and complications that occurred after TEVAR with subclavian revascularization. Notably, 61 patients (60.4%) required one or more intraoperative adjuncts in addition to C-SBP/ST, including subclavian embolization in 22, visceral/renal/iliac stent in 16, left common carotid/innominate stent in 15, simultaneous EVAR in 13, selective vertebral angiography or angioplasty, or both, in 4, arch debranching in 3, surgeon-modified aortic endograft in 3, transbrachial-femoral wire in 3, and atrial inflow balloon occlusion in 2.

The 30-day postoperative stroke, death, and combined stroke/death rates were, respectively, 8.9% (*n* = 9), 7.1% (*n* = 7), and 12.9% (*n* = 13). No significant difference in the rate of stroke or death was detected between various aortic coverage zone subgroups (*P* > .99). The combined stroke/death rate was lower in patients who did not require an intraoperative adjunct (5.9%) compared with those who did (16.4%, Fig 1), but this difference was not statistically significant. Details regarding TEVAR indication, urgency, and needed operative adjuncts for patients who had postoperative stroke are outlined in Table III.

**Subclavian revascularization and OD.** Thirty-eight subclavian revascularization procedures were performed for OD, with corresponding 30-day postoperative stroke,

**Table II.** Pathologic indication, operative details, and outcomes of patients undergoing subclavian revascularization for thoracic endovascular aortic repair (TEVAR) indications<sup>a</sup>

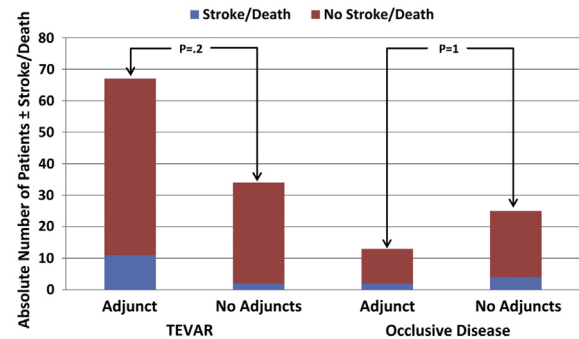
Feature	No. (%) or mean $\pm$ SD (n = 101)
ASA classification 3 or 4	100 (99)
Urgent/emergent	37 (36.6)
Pathology	
Aneurysm	48 (47.5)
Chronic dissection	18 (17.8)
Acute dissection	16 (15.8)
Other	16 (15.8)
Transection	3 (2.9)
Stents, No.	
1	39 (38.6)
2	36 (35.6)
$\geq 3$	26 (25.7)
Proximal coverage zone	
0	17 (16.8)
1	10 (9.9)
2	74 (73.2)
Conduit type	
Dacron	86 (85.1)
Polytetrafluoroethylene	15 (14.8)
Intraoperative adjunct	61 (60.4)
Any complication	36 (35.6)
Spinal cord ischemia	6 (5.9)
Stroke	9 (8.9)
Death	7 (6.9)
Length of stay, days	9.7 $\pm$ 10.3

ASA, American Society of Anesthesiologists.

<sup>a</sup>Note that 36% of cases were performed for urgent or emergent indications and 60% required some form of intraoperative adjunct to successfully complete the TEVAR.

death, and combined stroke/death rates of, respectively, 15.8% (n = 6), 2.6% (n = 1), and 15.8% (n = 6). Peri-procedural variables and outcomes of the OD C-SBP/ST subgroup are further delineated in Table IV. Specific indications for cervical reconstruction involving the subclavian artery included failed stent/arm fatigue, 49%; asymptomatic >80% internal carotid stenosis with concurrent subclavian occlusion and arm ischemia, 18%; symptomatic carotid or vertebral OD, or both, with severe proximal common carotid OD, 13%; redo bypass with arm ischemia, 8%; and coronary-subclavian steal, 5%. Among these patients, 13 (34.2%) required one or more adjunctive procedures, including simultaneous carotid endarterectomy or bypass in 7, retrograde common carotid/innominate stenting in 5, or vertebral artery reimplantation in 2. The rates of 30-day stroke, death, and combined stroke/death were not significantly different between patients who required an adjunctive revascularization procedure compared with those undergoing C-SBP/ST alone ( $P > .99$ , Fig 1).

Urgent or emergent presentations were common in OD patients (n = 17; 45%) and included cerebrovascular symptoms in seven, arm ischemia in seven, and cardiac symptoms in three. Stroke rate in the urgent patients was 29% compared with 5% of those undergoing elective



**Fig 1.** Thirty-day stroke/death rate after subclavian revascularization for thoracic endovascular aortic repair (TEVAR) or occlusive disease (OD) indications stratified by the need for adjunctive intervention. Although not statistically significant, TEVAR patients requiring adjunctive intervention in addition to subclavian revascularization appeared to have a clinical trend toward higher neurologic morbidity and mortality than those who did not (16.4% vs 5.9%). Incidence of stroke/death was similar in OD patients regardless of their need for intraoperative adjuncts (15.4% with and 16.0% without).

reconstruction ( $P = .05$ ). OD patients who suffered a stroke postoperatively had an overall greater number of comorbidities than the remainder of the cohort ( $6.5 \pm 2.8$  vs  $4.9 \pm 2.5$ ;  $P = .08$ ). For OD patients who had postoperative stroke, specifics regarding indication for cervical revascularization, urgency, and need for operative adjuncts are further detailed in Table V.

**Patency and reintervention.** Mean follow-up time was  $16.1 \pm 24.8$  months (median, 3.9) for the entire cohort,  $12.0 \pm 19.4$  months (median, 2.0 months) for TEVAR patients, and  $26.9 \pm 33.5$  months (median, 13.9 months) for OD patients. Radiographic follow-up time in patients with available imaging was  $14.5 \pm 21.1$  months (median, 6.4 months) for TEVAR patients and  $32.5 \pm 34.7$  months (median, 25.6 months) for OD patients. Figs 2 and 3 highlight the primary patency and freedom from reintervention after C-SBP/ST. The 1-year and 3-year primary patencies were, respectively, 93% and 73% for OD patients and 94% and 94% for TEVAR patients. Similarly, the corresponding 1-year and 3-year rates of freedom from reintervention were 93% and 73% for OD patients and 94% and 94% for TEVAR patients.

**Survival after subclavian revascularization.** Fig 4 depicts the overall 5-year survival for OD and TEVAR patients undergoing C-SBP/ST. For all patients, the estimated 1-year survival was 88% (95% confidence interval, 81%-93%) and the 5-year survival was 76% (95% confidence interval, 66%-83%). Corresponding 5-year actuarial survival estimates were 74% for TEVAR and 76% for OD patients ( $P = .4$ ).

**Multivariable analysis of stroke and death.** Multivariable logistic regression analysis was completed to identify factors predictive of 30-day stroke/death for all patients undergoing subclavian revascularization. C-SBP/ST performed as an adjunct to TEVAR, presence of



**Table III.** Details regarding the index thoracic endovascular aortic repair (TEVAR) indication, procedural details, stroke timing, distribution, and outcomes<sup>a</sup>

Patient	Indication	Urgency	Bypass operation	TEVAR adjunct	Stroke location/timing	Outcome
1	Thoracic aneurysm	Elective	L CCA-SCA; Pre-op	LSCA embolization; R iliac conduit	L cerebellar; POD#0	Death on POD#6
2	Kommerell's <sup>b</sup>	Elective	R CCA-SCA; Pre-op	None	Bilateral anterior hemisphere; POD#0	Full recovery
3	Thoracic aneurysm	Elective	R→L CCA-CCA + L CCA-SCA; Intra-op	R iliac conduit	Bilateral anterior hemisphere; POD#0	Death; 2.2 months
4	Thoracoabdominal aneurysm	Elective	Arch debranching; Pre-op	Direct aortic conduit	L MCA; POD#0	Residual R arm weakness; home
5	Thoracic aneurysm	Elective	L CCA-SCA; Intra-op LIMA salvage	R transbrachial femoral wire; R femoral TEA	R cerebellar; POD#2	Death; 2.6 months
6	Acute dissection	Urg/Symp	L CCA-SCA; Intra-op	Vertebral transposition	L cerebellar; POD#0	Death on POD#9
7	Chronic dissection/ aneurysm	Elective	L CCA-SCA; Pre-op	None	R MCA	Death on POD#15
8	Aortic coarctation pseudoaneurysm	Elective	L CCA-SCA transposition; Intra-op	R atrial inflow occlusion	R occipital; POD#14	Full recovery
9	Chronic dissection/ aneurysm	Elective	L CCA-SCA; Intra-op	L renal stent graft	L MCA; POD#1	Full recovery

CCA, Common carotid artery; L, left; LIMA, left internal mammary artery; MCA, middle cerebral artery; POD, postoperative day; R, right; SCA, subclavian artery; TEA, thromboendarterectomy.

<sup>a</sup>Five of the nine stroke patients (55.5%) died ≤3 months of the index TEVAR that required subclavian revascularization.

<sup>b</sup>Kommerell diverticulum (dysphagia lusoria).

**Table IV.** Indications, procedure-related details, and outcomes of patients with occlusive disease (OD) indications undergoing subclavian revascularization<sup>a</sup>

Feature	No. (%) or mean ± SD (n = 38)
ASA classification 3 or 4	35 (92.1)
Urgent/emergent	17 (44.7)
Previous subclavian stent	16 (42.1)
Redo bypass	9 (23.7)
Pathology	
OD	32 (84.2)
Hemodialysis access salvage	3 (7.8)
LIMA salvage	3 (7.8)
Conduit type	
Polytetrafluoroethylene	22 (57.9)
Dacron	7 (18.4)
Femoral vein	7 (18.4)
Saphenous vein	2 (5.3)
Intraoperative adjunct	13 (34.2)
Any complication	13 (34.2)
Stroke	6 (15.8)
Death	4 (10.5)
Length of stay, days	5.3 ± 9.5

ASA, American Society of Anesthesiologists; LIMA, left internal mammary artery; SD, standard deviation.

<sup>a</sup>The presentation was urgent or emergent in 44%, and 34% required adjunctive procedure.

preoperative renal insufficiency (defined as creatinine >1.8 mg/dL), and coronary artery disease (CAD; defined according to SVS reporting guidelines<sup>14-16</sup>) were included in the final model, which predicted the composite outcome

correctly in 90% of patients (area under the curve = 0.72). Renal insufficiency increased the risk of stroke/death 5.8-fold (95% CI, 1.8-fold to 18.50-fold;  $P = .003$ ), whereas CAD was associated with a 3.6-fold increase in the composite outcome (95% CI, 1.2-fold to 11.7-fold;  $P = .03$ ). TEVAR was included in the model but was not an independent predictor of stroke/death (odds ratio, 1.5;  $P = .5$ ).

## DISCUSSION

The results of this contemporary series of C-SBP/ST procedures performed in the endovascular era demonstrate a higher rate of stroke in OD patients compared with historical reports, with many patients having undergone previous endovascular or open interventions. This study also suggests that the perioperative stroke risk may be higher in TEVAR patients when subclavian revascularization is performed with other adjunctive therapies. Despite an increased rate of perioperative neurologic morbidity under these circumstances, patency of C-SBP is excellent, and long-term survival does not appear to be negatively affected by these complications.

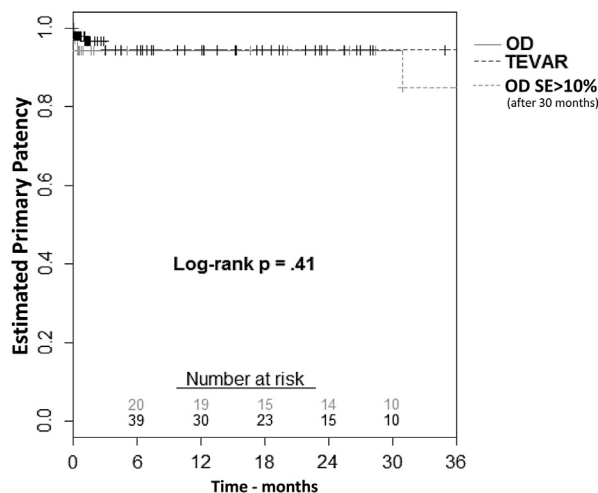
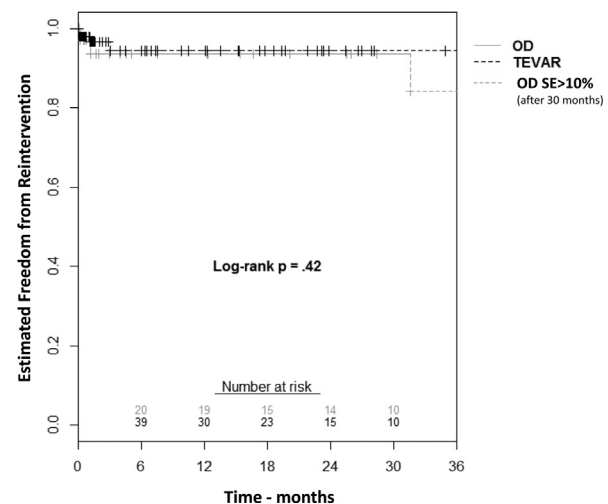
Significant subclavian artery OD (≥15 mm Hg inter-arm pressure difference) is estimated to be present in 2% to 7% of the general population; however, the true prevalence is not known because most lesions are found incidentally in asymptomatic patients.<sup>17-19</sup> Historically, direct repair of subclavian OD was performed through a thoracotomy,<sup>1,3</sup> but the high morbidity and mortality of this approach led to increased adoption of extra-anatomic

**Table V.** Details regarding the indication, technical conduct, stroke timing, distribution, and outcomes for patients experiencing a stroke after undergoing cervical reconstruction involving subclavian revascularization<sup>a</sup>

Patient	Indication	Urgency	Bypass operation	Adjunct	Stroke location/timing	Outcome
1	Right subclavian occlusion, innominate pseudoaneurysm, failed stent for arm fatigue	Urg/symp	R CCA-SCA	Innominate stent graft subclavian embolization	R MCA; POD#0	R leg weakness, living at home
2	Left carotid stump syndrome and vertebral stenosis	Urg/symp	L SCA-ICA	L CEA/vertebral reimplant	L pontine; POD#0	Full recovery
3	Global hypoperfusion	Elective	Redo L CCA-SCA	L CEA	L MCA; POD#0	Death; POD#14
4	Left carotid occlusion	Urg/symp	L SCA-CCA	None	L MCA; POD#24	Full recovery
5	Global hypoperfusion	Elective	SCA-ICA	None	R occipital; POD#14	Full recovery
6	VBI	Elective	L CCA-SCA	None	L cerebellar; POD#0	Full recovery

CCA, Common carotid artery; CEA, carotid endarterectomy; ICA, internal carotid artery; L, left; MCA, middle cerebral artery; OD, occlusive disease; POD, postoperative day; SCA, subclavian artery; VBI, vertebrobasilar insufficiency.

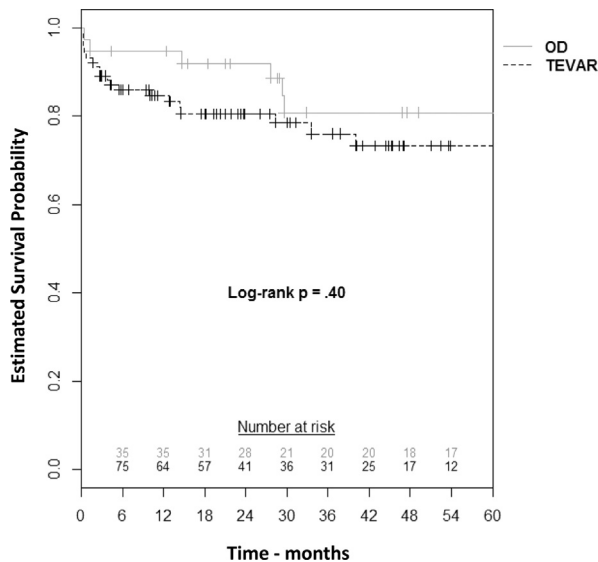
<sup>a</sup>Notably, three patients required the subclavian artery as the donor vessel to the bypass due to extracranial carotid OD. One of the six patients (16.7%) died postoperatively; however, the remaining patients experienced neurologic recovery.

**Fig 2.** Primary patency of subclavian revascularization is shown for thoracic endovascular aortic repair (TEVAR) and occlusive disease (OD) indications. The two groups have equivalent 1-year and 3-year primary patency. SE, Standard error.**Fig 3.** Freedom from reintervention after subclavian revascularization for thoracic endovascular aortic repair (TEVAR) and occlusive disease (OD) indications is depicted. No difference in the need for reintervention is noted at 1 and 3 years between the two groups. SE, Standard error.

bypass methods, including carotid-subclavian, axilloaxillary bypass, and carotid-ST.<sup>4,5,7</sup> Indeed, C-SBP/ST quickly supplanted virtually all direct or alternative extra-anatomic (eg axilloaxillary or femoroaxillary bypass) strategies for open surgical reconstruction of subclavian OD after multiple reports documented low 30-day major morbidity (2%-15%) and mortality (0%-2%) as well as excellent 5-year primary patency (82%-95%).<sup>4,5,10,18,20</sup>

The outcomes after C-SBP/ST have most commonly been described in the context of an isolated subclavian revascularization without adjunctive procedures. Morbidity in that setting is primarily related to cranial nerve injury (1%-11%), cardiovascular events (1%-8%), hematoma (0.2%-2%), lymph leak (0%-9%), and embolic complications (0%-3%).<sup>5,20</sup> The stroke risk with an isolated C-SBP

without adjunctive procedures has consistently been reported to be 0% to 6%.<sup>5,20-22</sup> Of note, simultaneous significant (>70%) vertebral or carotid OD, or both, is reportedly present in 58% to 75% of patients,<sup>21</sup> which can often necessitate more complex arterial reconstructions. Staged or concomitant carotid reconstruction with C-SBP/ST has been shown to increase the perioperative stroke risk. Risty et al<sup>23</sup> reported a review of 12 studies, comprising 765 patients, with a 30-day stroke rate of 4.7% when C-SBP/ST was performed with concomitant ipsilateral CEA compared with 0.3% when C-SBP/ST was performed alone ( $P < .001$ ). Further, Sullivan et al<sup>24</sup> reported a 14% rate of stroke in patients with tandem carotid bifurcation and proximal common carotid OD



**Fig 4.** Overall patient survival after subclavian revascularization for thoracic endovascular aortic repair (TEVAR) and occlusive disease (OD) indications is demonstrated. Notably, despite elevated rates of neurologic morbidity compared with historical controls, 5-year survival is good and equivalent between the two cohorts.

who underwent hybrid open CEA plus retrograde carotid/innominate stenting. In our series, 11 patients (28.9%) similarly required simultaneous CEA or carotid/innominate stent placement, or both, along with their C-SBP, and two (18.2%) sustained nondisabling strokes, indicating that the addition of adjuncts and procedural complexity, not surprisingly, increases the risk of these procedures.

With the advent of endoluminal therapies in the 1990s, open surgical reconstruction for supra-aortic trunk disease has been increasingly performed for endovascular failures or for patients with complex anatomy.<sup>10</sup> This trend is evident in our series; prior subclavian stent placement or C-SBP, or both, was unsuccessful in 16 patients (42%). The negative effect of prior failed endovascular intervention on C-SBP is not known, but notably, two of the three postoperative graft thrombosis events in our OD cohort occurred in patients whose previous endovascular intervention was not successful. Despite this, the patency of C-SBP/ST was excellent in our series of OD patients, with primary patency of 93% at 1 year and 73% at 3 years. Although these estimates seem lower than those after subclavian revascularization with TEVAR (94% and 94%, respectively), the accuracy of the 3-year OD primary patency estimates were limited by small numbers and a standard error >10% beyond 30 months.

The relatively high rate in our series of prior failed subclavian intervention and the need for simultaneous carotid or vertebral reconstruction, or both, suggests that these patients have more advanced disease and greater atherosclerotic disease burden than those in historical series. In addition, a substantial proportion of our OD

patients (45%) presented urgently with cerebrovascular, cardiac, or arm ischemia symptoms, which likely contributed to the higher-than-expected perioperative stroke rates. Indeed, 29% of OD patients who underwent urgent C-SBP had a postoperative stroke compared with 5% of those undergoing elective reconstruction, which was significantly different ( $P = .05$ ). Further, OD patients who sustained a postoperative stroke had an overall greater number of comorbidities than the rest of the cohort ( $6.5 \pm 2.8$  vs  $4.9 \pm 2.5$ ;  $P = .08$ ).

TEVAR has become an increasingly common indication for C-SBP/ST during the last decade, and up to 40% of all TEVAR patients require LSA coverage for successful repair. Coverage of the subclavian artery has been associated with a 3% to 8% perioperative stroke, spinal cord ischemia, or death rate.<sup>25</sup> The 2010 SVS consensus statement<sup>11</sup> supports preemptive subclavian revascularization, but this suggestion is based on low-quality evidence and remains controversial. Our bias is to revascularize the subclavian artery, particularly in the patient who is felt to be at high risk for spinal cord ischemia (eg, extensive TEVAR coverage, prior infrarenal aortic repair, etc) or who has a dominant left vertebral artery. In patients with short aortic coverage (<150 mm) and a nondominant left vertebral artery with no other indications for revascularization, we will cover the LSA without revascularization.

Owing to these considerations, our practice has experienced a 2.5-fold greater use of C-SBP/ST for TEVAR compared with OD indications during a 10-year interval. Again, conflicting data exist regarding stroke risk with the addition of C-SBP/ST to TEVAR, and stroke after TEVAR is known to portend a particularly poor prognosis, with in-hospital mortality rates ranging from 5% to 33%.<sup>26-28</sup> Some have endorsed a more selective LSA revascularization strategy because of the concern of elevated stroke risk.<sup>29,30</sup>

In our series, the perioperative stroke and death rates were, respectively, 8.9% and 7% after TEVAR with C-SBP/ST. Although somewhat higher than previously reported, the mortality rate may be explained by the significant proportion of patients (37%) with emergent/ruptured or urgent/symptomatic presentations for a variety of indications, including acute dissection and contained aneurysm rupture, among others. In addition, 60% of TEVAR patients required additional intraoperative adjuncts along with C-SBP/ST. A need for other intraoperative adjuncts is likely a marker of more extensive aortic disease and thus may be associated with increased neurologic risk. Patients who required additional adjuncts had a trend toward an increased perioperative stroke/death rate (16.4%) compared with those who did not (5.9%;  $P = .2$ ).

Independent predictors of postoperative stroke/death identified among the entire cohort of C-SBP/ST patients were preoperative renal insufficiency and coronary artery disease (CAD), increasing the risk of the composite outcome by nearly sixfold and fourfold, respectively. Interestingly, the surgical indication for C-SBP/ST (TEVAR

vs OD) was not a significant predictor of the outcome. Instead, the occurrence of postoperative stroke and death seemed to be primarily dictated by patient-related factors and the overall complexity of their procedure.

This study has several limitations, including that this is a single-center, retrospective study with limited patient numbers and events for analysis. This leads to the possibility of type II error and limits the conclusions we can draw from the multivariable analysis. Moreover, multiple indications and procedural urgency categories were analyzed, which might have contributed additional confounding to the observed results.

Although the results of this analysis will undoubtedly raise concerns, particularly regarding the outcome of the subclavian revascularization for OD subgroup, we highlight that the evolution of the type and complexity of the procedures represented in this report are vastly different than those for historical controls.

Finally, there was no standardized treatment algorithm dictating when C-SBP/ST was performed as an adjunct to TEVAR and when carotid/vertebral reconstruction was performed as an adjunct to C-SBP/ST in OD patients. This further limits the conclusions that can be made regarding the effects that these adjuncts may have on outcomes.

## CONCLUSIONS

Stroke risk in this contemporary series of C-SBP/ST performed for TEVAR and OD may be higher than previously reported in historical series. However, this seems to be attributable primarily to patient-related factors and the complexity of the procedure in both TEVAR and OD patients. Despite the short-term morbidity, excellent bypass durability and equivalent long-term patient survival can be anticipated.

## AUTHOR CONTRIBUTIONS

Conception and design: SS, AB

Analysis and interpretation: SS, CC

Data collection: SS, SP

Writing the article: SS, CC, AB

Critical revision of the article: SS, CC, SP, RF, SB, TH, AB

Final approval of the article: SS, CC, SP, RF, SB, TH, AB

Statistical analysis: CC

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Overall responsibility: SS

SS and CC participated equally and share first authorship.

## REFERENCES

- Crawford ES, De Bakey ME, Morris GC Jr, Howell JF. Surgical treatment of occlusion of the innominate, common carotid, and subclavian arteries: a 10 year experience. *Surgery* 1969;65:17-31.
- Edwards WH Jr, Tapper SS, Edwards WH Sr, Mulherin JL Jr, Martin RS 3rd, Jenkins JM. Subclavian revascularization. A quarter century experience. *Ann Surg* 1994;219:673-7; discussion: 677-8.
- Diethrich EB, Garrett HE, Ameriso J, Crawford ES, el-Bayar M, De Bakey ME. Occlusive disease of the common carotid and subclavian arteries treated by carotid-subclavian bypass. Analysis of 125 cases. *Am J Surg* 1967;114:800-8.
- Perler BA, Williams GM. Carotid-subclavian bypass—a decade of experience. *J Vasc Surg* 1990;12:716-22; discussion: 722-3.
- Vitti MJ, Thompson BW, Read RC, Gagne PJ, Barone GW, Barnes RW, et al. Carotid-subclavian bypass: a twenty-two-year experience. *J Vasc Surg* 1994;20:411-7; discussion: 417-8.
- Takach TJ, Reul GJ, Duncan JM, Krajcer Z, Livesay JJ, Gregoric ID, et al. Concomitant brachiocephalic and coronary artery disease: outcome and decision analysis. *Ann Thorac Surg* 2005;80:564-9.
- Chang JB, Stein TA, Liu JP, Dunn ME. Long-term results with axillo-axillary bypass grafts for symptomatic subclavian artery insufficiency. *J Vasc Surg* 1997;25:173-8.
- Takach TJ, Reul GJ, Cooley DA, Duncan JM, Livesay JJ, Gregoric ID, et al. Brachiocephalic reconstruction I: operative and long-term results for complex disease. *J Vasc Surg* 2005;42:47-54.
- Sixt S, Rastan A, Schwarzwald U, Burgelin K, Noory E, Schwarz T, et al. Results after balloon angioplasty or stenting of atherosclerotic subclavian artery obstruction. *Catheter Cardiovasc Interv* 2009;73:395-403.
- Palchik E, Bakken AM, Wolford HY, Saad WE, Davies MG. Subclavian artery revascularization: an outcome analysis based on mode of therapy and presenting symptoms. *Ann Vasc Surg* 2008;22:70-8.
- Matsumura JS, Rizvi AZ. Left subclavian artery revascularization: Society for Vascular Surgery practice guidelines. *J Vasc Surg* 2010;52:65S-70S.
- Buth J, Harris PL, Hobo R, van Eps R, Cuypers P, Duijm L, et al. Neurologic complications associated with endovascular repair of thoracic aortic pathology: incidence and risk factors. A study from the European Collaborators on Stent/Graft Techniques for Aortic Aneurysm Repair (EUROSTAR) registry. *J Vasc Surg* 2007;46:1103-10; discussion: 1110-1.
- Woo EY, Carpenter JP, Jackson BM, Pochettino A, Bavaria JE, Szeto WY, et al. Left subclavian artery coverage during thoracic endovascular aortic repair: a single-center experience. *J Vasc Surg* 2008;48:555-60.
- Rutherford RB, Baker JD, Ernst C, Johnston KW, Porter JM, Ahn S, et al. Jones Recommended standards for reports dealing with lower extremity ischemia: revised version. *J Vasc Surg* 1997;26:517-38.
- Chaikof EL, Fillinger MF, Matsumura JS, Rutherford RB, White GH, Blankensteijn JD, et al. Identifying and grading factors that modify the outcome of endovascular aortic aneurysm repair. *J Vasc Surg* 2002;35:1061-6.
- Fillinger MF, Greenberg RK, McKinsey JF, Chaikof EL. Reporting standards for thoracic endovascular aortic repair (TEVAR). *J Vasc Surg* 2010;52:1022-3; 1033 e1015.
- Berguer R, Morasch MD, Kline RA, Kazmers A, Friedland MS. Cervical reconstruction of the supra-aortic trunks: a 16-year experience. *J Vasc Surg* 1999;29:239-46; discussion: 246-8.
- AbuRahma AF, Bates MC, Stone PA, Dyer B, Armistead L, Scott Dean L, et al. Angioplasty and stenting versus carotid-subclavian bypass for the treatment of isolated subclavian artery disease. *J Endovasc Ther* 2007;14:698-704.
- Shadman R, Criqui MH, Bundens WP, Fronck A, Denenberg JO, Gamst AC, et al. Subclavian artery stenosis: prevalence, risk factors, and association with cardiovascular diseases. *J Am Coll Cardiol* 2004;44:618-23.
- Cina CS, Safar HA, Lagana A, Arena G, Clase CM. Subclavian carotid transposition and bypass grafting: consecutive cohort study and systematic review. *J Vasc Surg* 2002;35:422-9.
- Sterpetti AV, Schultz RD, Farina C, Feldhaus RJ. Subclavian artery revascularization: a comparison between carotid-subclavian artery bypass and subclavian-carotid transposition. *Surgery* 1989;106:624-31; discussion: 631-2.
- Sim EK, van Son JA, Edwards WD, Julsrud PR, Puga FJ. Coronary artery anatomy in complete transposition of the great arteries. *Ann Thorac Surg* 1994;57:890-4.



23. Risty GM, Cogbill TH, Davis CA, Lambert PJ. Carotid-subclavian arterial reconstruction: concomitant ipsilateral carotid endarterectomy increases risk of perioperative stroke. *Surgery* 2007;142:393-7.
24. Sullivan TM, Gray BH, Bacharach JM, Perl J 2nd, Childs MB, Modzelewski L, et al. Angioplasty and primary stenting of the subclavian, innominate, and common carotid arteries in 83 patients. *J Vasc Surg* 1998;28:1059-65.
25. Rizvi AZ, Murad MH, Fairman RM, Erwin PJ, Montori VM. The effect of left subclavian artery coverage on morbidity and mortality in patients undergoing endovascular thoracic aortic interventions: a systematic review and meta-analysis. *J Vasc Surg* 2009;50:1159-69.
26. Gutsche JT, Cheung AT, McGarvey ML, Moser WG, Szeto W, Carpenter JP, et al. Risk factors for perioperative stroke after thoracic endovascular aortic repair. *Ann Thorac Surg* 2007;84:1195-200; discussion: 1200.
27. Kotelis D, Bischoff MS, Jobst B, von Tengg-Koblighk H, Hinz U, Geisbusch P, et al. Morphological risk factors of stroke during thoracic endovascular aortic repair. *Langenbecks Arch Surg* 2012;397:1267-73.
28. Ullery BW, McGarvey M, Cheung AT, Fairman RM, Jackson BM, Woo EY, et al. Vascular distribution of stroke and its relationship to perioperative mortality and neurologic outcome after thoracic endovascular aortic repair. *J Vasc Surg* 2012;56:1510-7.
29. Maldonado TS, Dexter D, Rockman CB, Veith FJ, Garg K, Arko F, et al. Left subclavian artery coverage during thoracic endovascular aortic aneurysm repair does not mandate revascularization. *J Vasc Surg* 2013;57:116-24.
30. Lee TC, Andersen ND, Williams JB, Bhattacharya SD, McCann RL, Hughes GC. Results with a selective revascularization strategy for left subclavian artery coverage during thoracic endovascular aortic repair. *Ann Thorac Surg* 2011;92:97-102; discussion: 102-3.

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